Lecture-9A — Gradient-Echo Sequences
Balanced-SSFP Dynamics

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Learning Objectives

• Explain geometric derivation of bSSFP dynamics
• Describe characteristics of the bSSFP signal vs frequency
• Explain phase cycling and why it is useful
Short-TR Gradient Echo

- Rapid, efficient 2D/3D imaging
- High-resolution with minimal blurring
- **Steady states and equilibrium**
  - Pushing a swing (with friction)
  - Heating a room (with a window open)
  - Exciting magnetization (with relaxation)

Short TR sequences require consideration of steady states
Outline: Gradient Echo Sequences

- Gradient Echo = No spin echo!
- Spoiling Types
- Properties

Contrast is based primarily on the end-of-TR action
Balanced Steady-State Free Precession (bSSFP)

In balanced SSFP, all gradients are designed to have zero area over TR.
Question 1: Balanced SSFP

- Relaxation is quite small
- Back & forth tip by 60°
- Symmetric?
- +/- 30° from Mz
- Difficult to say much about the length

• What do you think happens here?
Balanced SSFP: Steady State Formation

- Same unique periodic steady state
- **Transient** paths differ based on initial state

After many sequence repetitions a steady state forms
Simple Case: No precession

- Intuition: Relaxation does not affect direction much
- RF rotations must balance each other

Basic intuition is that we tip back-and-forth in the steady-state, with small changes based on the Bloch equation.
Steady State: No Precession
Off-Resonance: Precession
Increasing Precession
The magnetization moves on the surface of an ellipsoid, with the RF flipping between 2 planes an angle $\alpha$ apart.
Signal Solution - On Resonance

- Relaxation does not change length:
  \[ \frac{dM}{dt} \cdot M = 0 \]

Substitute from Bloch equation:

\[ \frac{-M_x^2 - M_y^2}{T_2} + \frac{M_0 - M_z}{T_1}M_z = 0 \]

Multiply by \(T_1\) and rearrange:

\[
\left( M_z - \frac{M_0}{2} \right)^2 + \frac{M_x^2 + M_y^2}{T_2/T_1} = \left( \frac{M_0}{2} \right)^2
\]

- Ellipse, eccentricity \(\sqrt{T_2/T_1}\), width \(M_0/2\sqrt{T_2/T_1}\)
- Intersection based on \(\alpha\)
- \(T_2/T_1\) contrast

Assuming the magnetization length does not change leads to an ellipsoidal solution for the signal. Hargreaves, JMRI 2012
Question 2: Signal levels

With no off-resonance, $T_1 = T_2$, what is the transverse magnetization (signal) for $\alpha = 90^\circ$?

- $T_1 = T_2$: Circular distribution!
- $90^\circ$: Full extent
- Signal = $M_0/2$

What if $\alpha = 60^\circ$?

- Signal = $M_0/2 \sin(120^\circ/2) \approx 0.43M_0$
RF Nutation and Precession

- RF is balanced by relaxation and precession
- Length is still relatively unchanged over TR
- Ignore relaxation for now…

\[
\tan(\alpha/2) = \tan(\beta/2) \cos(\phi/2)
\]

Schmitt MRM 2006, Zun, ISMRM 2006
Precession and “Effective flip angle”

- \( \tan \left( \alpha/2 \right) = \tan \left( \beta/2 \right) \cos \left( \phi/2 \right) \) \hspace{5mm} (\beta \geq \alpha)
- Larger precession (\( \phi \)) gives a larger “effective flip,” \( \beta \)
- Can replace flip (\( \alpha \)) with effective flip (\( \beta \)) for all calculations
- Limiting case (\( \bullet \)) where \( \beta = 180^\circ \)
Signal vs Precession/Frequency

Signal depends on many factors:
- Resonant frequency
- T1, T2 (contrast)
- RF flip / phase
- TR, TE

As $|\phi|$ the steady-state moves down the ellipsoid. We can plot signal vs frequency ($\phi/\text{TR}$)

Freeman 1971
The transverse magnetization moves from an elliptical to refocused to elliptical distribution over TR.
Flip Angle Effects

As the flip angle increases, less of the ellipsoid is used and the signal does not always reach the peak.
bSSFP Dark Bands

- Must limit precession:
  Short TR

- Limits resolution

The signal-vs-frequency variation causes dark bands. Freeman 1971
Phase Cycling

A linear phase increment $\phi$ (per TR) shifts the profile by $(\phi/2\pi)/\text{TR}$. Hinshaw 1976

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Question 3: Phase Cycling

With TR=5ms, where are signal nulls if $\alpha$ sign is alternated?

A. 100 Hz, -100 Hz

What if $\alpha$ sign is constant?

B. 0 Hz, -200 Hz, 200 Hz
Combined Acquisitions

Alternating RF  Combined Acquisition

Zur 1990, Haacke 1990
bSSFP Steady-State: Summary

- Ellipsoidal distribution: shape given by T2/T1
- Path depends on flip angle and precession
- Signal very sensitive to resonant frequency
- TrueFISP, FIESTA, Balanced FFE, BASG, True SSFP
What are mathematical descriptions of Balanced SSFP dynamics?
Rad229 – MRI Signals and Sequences

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